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Published in:
Detaled Program

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Flow tilt angle measurements from the ground

Jakob Mann[1], Ebba Dellwik[1], Ferhat Bingöl[1], Michael S. Courtney[1] and Dimitri Foussekis[2]
[1]Risø DTU National Laboratory of Sustainable Energy, Wind Energy Department, Denmark
[2]CRES, Centre for Renewable Energy Sources, Athens, Greece

1 INTRODUCTION

Eddy covariance measurements, which provide a direct method of measuring turbulent fluxes of carbon to and from the land surface, are the main component in the FluxNet (Baldocchi, 2001) network of towers for assessing the terrestrial carbon balance. However, also the mean motion of the air may result in a net flux. This has been recognized in many studies on advection (Lee, 1998; Finnigan, 1999; Dellwik et al., 2010).

Dellwik et al. (2010) analyzed mean flow tilt angle and vertical velocities from sonic anemometers near a forest edge and found that instrumental precision is severely limited due to flow distortion. Especially at the highly turbulent forested sites, eddies hit the anemometer at steep angles of attack for which it is usually not calibrated.

Here we want to assess the capabilities of a lidar for measuring the mean vertical velocity. Deriving flow tilt angles and mean vertical velocities from such a remote sensing instrument has several advantages compared to sonic anemometry; there is no flow distortion caused by the instrument itself, there are no temperature effects and the instrument misalignment can be corrected for by comparing tilt estimates at various heights. Contrary to mast-based instruments, the lidar measures the wind field with the exact same alignment error at a multitude of heights.

Disadvantages with estimating vertical velocities from a lidar compared to mast-based measurements are slightly increased levels of statistical errors due to limited sampling time, because the sampling is disjunct and a requirement for homogeneous flow. The estimated mean vertical velocity is biased if the flow over the scanned circle is not homogeneous.

2 THEORY

2.1 Flow tilt angles over a forest

The anticipated flow over a perfect two-dimensional fetch-limited forest is sketched in Fig.1:

1. Edge phase: The flow accelerates above the canopy and decelerates within. Both above and below the crowns, the mean vertical velocity W is positive.

2. Deceleration phase above the canopy: At canopy height h_C, the mean wind speed U starts decelerating due to the high roughness of the forest. In this phase, W is slightly positive within and just above the canopy.

3. Equilibrium phase: There is no net vertical motion.

4. Exit phase: The starting point of the exit phase occurs where the flow in the canopy starts accelerating $\frac{dU_C}{dx} > 0$, due to the presence of the downstream edge. At canopy height, W turns negative.

2.2 Lidar error caused by inhomogeneous mean flow

The wind vector measured by a lidar is derived under the assumption a horizontally homogeneous flow, but here we allow for a linear variation in space.

Assume the mean wind field $\boldsymbol{U} = (U, V, W) = (U_1, U_2, U_3)$ to vary linearly

$$U_i(\boldsymbol{x}) = U_i(\boldsymbol{0}) + x_j \frac{\partial U_i}{\partial x_j} \tag{1}$$

over a volume enclosing the lidar scanning circle. The origo of the coordinate system $\boldsymbol{x} = \boldsymbol{0}$ is the center of the scanning circle elevated by h over the instrument.

Following Bingöl et al. (2009) it can then be shown that in the presence of a linear deviation from homogeneity the vertical wind estimated from the lidar is:

$$W_{\text{lidar}} = W - \frac{h}{2} \tan^2 \varphi \frac{\partial W}{\partial z} \quad . \tag{2}$$

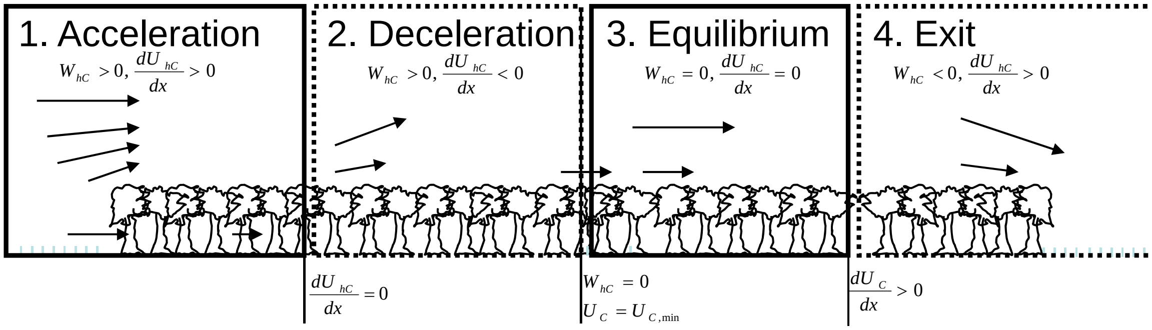

Figure 1: Sketch of flow downstream of a forest edge.

The error in W caused by the inhomogeneity will vanish for high altitudes, since $0.5h\partial W/\partial z$ approaches zero monotonously with height.

3 EXPERIMENTS

3.1 Sites

Three Danish sites were investigated; the forest site Sorø, the steep terrain site Bolund and the coastal flat site at Høvsøre. The Sorø site is described in detail in Dellwik et al. (2010). It is a typical Danish beech forest of limited extent ($\approx$ 2 x 1 km) containing clearings, see Fig. 2. A Solent R2 (Gill Instruments Ltd.) was mounted at 48m height in the mast, thereby matching the lowest focus distance of the lidar.

The Høvsøre site is a very flat site with low vegetation, where zero mean flow tilt angles are expected. The southernmost mast, used in this study, is the most well equipped with cup anemometers at 10, 40, 60, 80, 100, and 116.5 m and USA-1 scientific sonic anemometers (Metek GmbH) at 10, 20, 40, 60, 80, and 100 m. More information about the site may be found in Smith et al. (2006).

Bolund is a peninsula, where flow angles should vary due to the steep terrain slopes. It is 12m high and extends 130m in the W-E direction and 75m in the N-S direction (Fig.2). During the Bolund experiment, ten masts were operated. The lidar was located 8.5m to the south of mast 2 near the edge of the escarpment. Mast 2 was instrumented with five USA-1 basic anemometers (Metek GmbH.) at 1.1, 2.1, 3.6, 5.1 and 9.1 m height as well as two cup anemometers at 9.1 and 11.1 m height.

3.2 Lidar instrumentation

The durations of the experiments, measurement heights and lidar types are listed in Table 1. The ZephIR measures three revolutions at each measurement height, where each revolution takes about one second. The shift between heights also takes about 1s. A whole measurement cycle therefore takes about $n\times$4s where n is the number of measurement heights.

3.3 Results from the flat site: Høvsøre

The data shown in Fig.3 (top) are 30 minutes averages of the vertical velocity measured by the ZephIR close to the meteorological mast at Høvsøre as a function of wind direction. Wind coming from the north may be disturbed by the five large turbines on the test stand, but between the gray vertical lines the influence from the turbines should be negligible. The mean vertical wind speed was close to zero for all directions and heights, and the scatter around zero on the half hour values is between 0.25° and 0.5°.

In Fig. 3 (bottom), the corresponding mean flow tilt angles at 100 m from the sonic anemometers are shown. They have an off-set of $-0.5°$.

The scatter, which is an estimate of the statistical error, from the sonic anemometers and the lidar is of similar size, despite the fact that the sampling of the lidar is disjunct and in absolute time only covers 30/n minutes at each sampling height.

3.4 The complex site: Bolund

A comparison of mean flow tilt angles from the lidar and the 9.1 m sonic anemometer as a function of wind direction is shown in Fig.4. During the

Site	Lidar	Duration of experiment	Measurement height (m)
Sorø	ZephIR prototype	2006 11 15 - 2007 01 06	48, 57, 65, 76, 92, 113, 175
Høvsøre	ZephIR Commercial	2009 01 08 - 2009 11 02	40, 60, 80, 100, 116
Bolund	ZephIR Commercial	2008 02 01 - 2008 02 05	11, 20, 50, 100, 300

Table 1: Overview of lidar experiments.

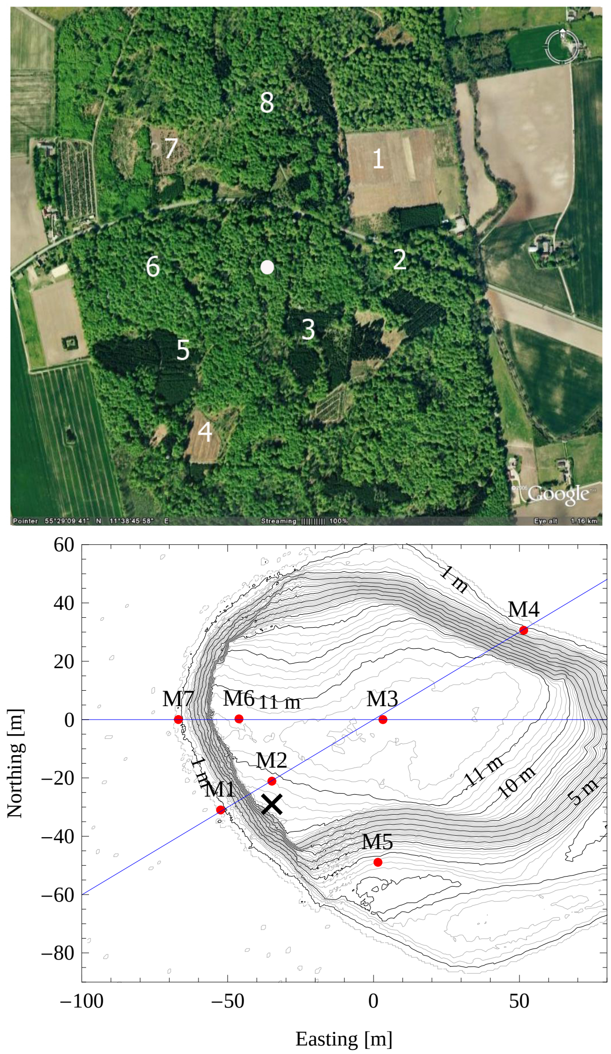

Figure 2: *Top:* The Sorø site (white dot). The numbers refer to the various clearing and tree types (Dellwik et al., 2010).*Bottom:* Map with masts positions at the Bolund experiment. The ZephIR lidar was located at the cross in the map, 8.5m to the south of mast 2 and only 3m from the escarpment.

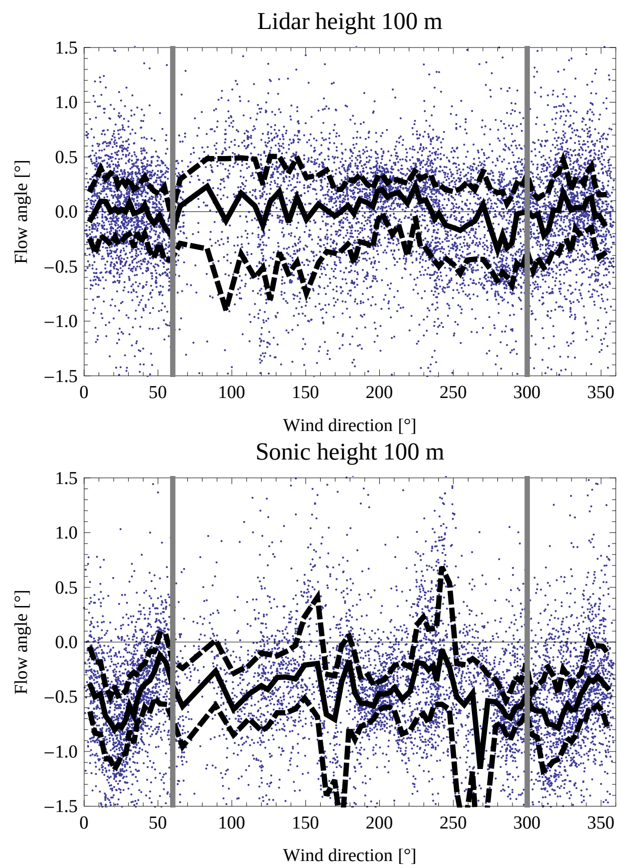

Figure 3: Comparison of lidar (top) and sonic (bottom) at Høvsøre using all data. Each point in the graphs signifies a 30 minute mean value, the full line is the median and the dashed lines represent the 25% and 75% quartiles.

five-day lidar experiment, wind directions were predominantly from South-West. Both the 300m and 100m focus distances show flow angles very close to zero, and the influence from the Bolund escarpment (western edge) is clearly visible for the lower focus distances. The shape of the wind direction response is similar for the lidar and the 9.1 m sonic anemometer, but the tilt angles measured by the sonic anemometer are considerably smaller in the interval $[160°, 290°]$ with a maximum around 4.5° compared to around 9° for the lidar at 11m focus height.

Eqn.2 was used to estimate the error to approximately $+1°$ at the 11m focus distance at the Bolund site, using the difference between the flow angles at 11m and 20m.

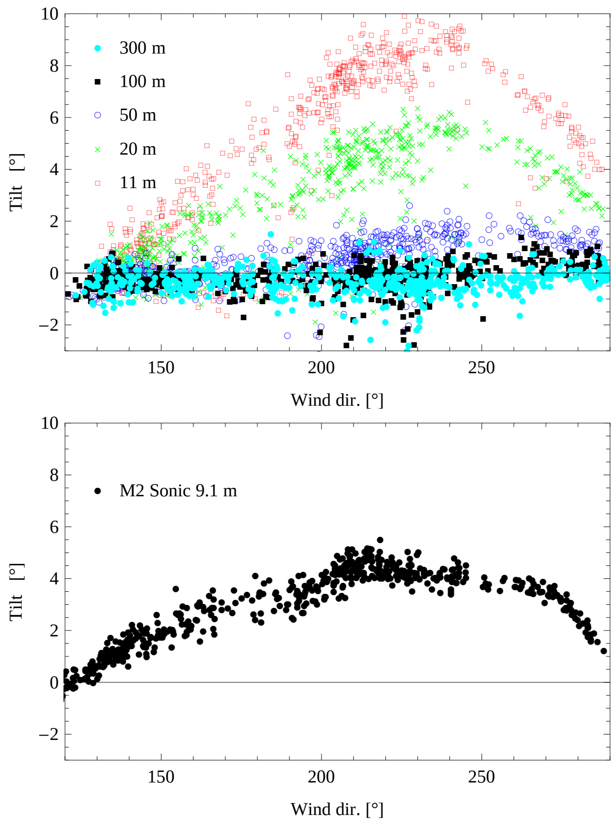

Figure 4: Comparison of lidar (top) and sonic (bottom) 30 minute mean flow tilt angles at Bolund using all data.

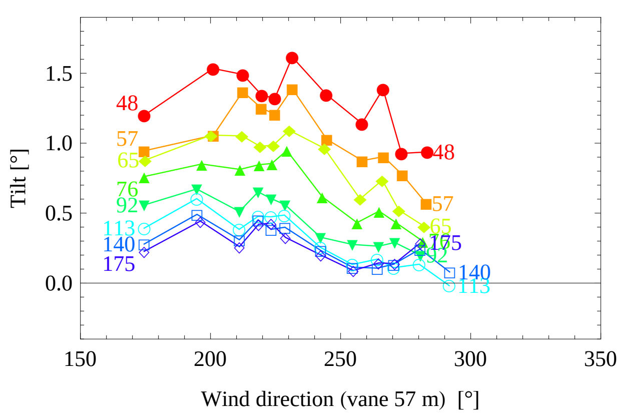

Figure 5: Mean flow tilt angles measured by lidar at Sorø, all measurement heights.

3.5 The forest site: Sorø

Mean flow tilt angles as a function of wind direction during the several months long campaign at the Sorø site are shown in Fig.5. Because of a limitation of the variation in wind directions during the experiment, it was hard to deduce whether the lidar was slightly tilted with respect to vertical. As for the Bolund results, the flow tilt angles decrease monotonously with height.

4 CONCLUSION

The ZephIR Doppler wind lidar was tested for its ability to measure mean flow tilt angles over forest. Since the mean flow tilt angles over the forest are expected to be small, the method was evaluated at two reference sites: the very flat, non-forested site, Høvsøre, and the steep hill Bolund. At Høvsøre, the lidar measured tilt angles very near zero, whereas the two sonic anemometers used for comparison showed a negative off-set. The systematic error of the Høvsøre lidar was evaluated to much less than 0.5°. The scatter around the median, which reflects the statistical error due to limited sampling time, was similar for sonic anemometers and the lidar. For the Bolund site, flow angles up 10° was measured with the lidar. The high flow angles were measured in the wind direction where the flow is the most inhomogeneous. By using the measured lidar gradient, the systematic error due to the flow inhomogeneity was estimated to +1°. Finally at the Sorø forest site the lidar measured positive flow angles of around 1.5° at the lowest measurement height (48m) and between 0.1° and 0.4° at the highest measurement level (175m). The systematic error due to the flow inhomogeneity was estimated to less than 0.2°. Sonic results are more dubious. The high level of turbulence at the forest site was reflected in higher statistical uncertainty. Lidar anemometry can provide consistent estimates of mean flow tilt angles also for the very turbulent forest flow. In general, the results from all sites pointed to the high accuracy of the lidar.

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